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**UNSTEADY TRANSONIC FLOWS  
IN A TWO-DIMENSIONAL DIFFUSER**

**M. Sajben  
T. J. Bogar  
J. C. Kroutil**

McDonnell Douglas Research Laboratories  
St. Louis, Missouri 63166

31 March 1982  
Final Technical Report for Period 1 April 1977 - 31 March 1982

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Transonic flow	Pressure fluctuations									
Flowfield oscillations	Inlet flow distortion									
Two-dimensional model	Laboratory simulation tests									
Air-breathing propulsion systems										
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  <p>Nominally two-dimensional flows in two convergent-divergent diffuser models were investigated experimentally. The flows contained a normal shock downstream of the throat with pre-shock Mach numbers ranging to 1.4. Self-sustaining fluctuations occurred invariably and were closely investigated. Steady and fluctuating wall and midstream pressures were measured; high-speed schlieren photography was extensively employed. Shock displacement histories were measured with a line-scan camera technique.</p>										

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20. ABSTRACT (continued)

The effects of initial boundary-layer thickness were found to exert a moderate influence on steady and dynamic flow properties. The influence of boundary-layer thickness was more pronounced when the flows were free of shock-induced separation.

Natural shock oscillation frequencies were determined and were found to scale inversely with channel length if the flow was attached. Up to three harmonics were observed, the frequencies of which were well predicted by one-dimensional acoustic theory. For shock-induced separation, the frequencies were independent of channel length and appeared to scale with the distance from the shock to the location where the boundary layers from the opposite walls merged.

Forced oscillations were induced by mechanical modulation of the exit cross-sectional area. The pressure disturbance propagates nearly as a one-dimensional acoustic wave. However, the overall structure of the disturbance pattern within the channel is determined by the characteristics of the pressure-wave reflection off the shock. The type of the reflection differs between the weak (attached) and strong (shock-induced separation) shock cases.

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### Preface

This final report summarizes a research program performed by the McDonnell Douglas Research Laboratories, St. Louis, Missouri, on unsteady transonic flows in two-dimensional diffusers. The research was conducted under Contract No. F49620-77-C-0082 for the Air Force of Scientific Research. The performance period was 1 April 1977 to 31 March 1982.

The principal investigator was Dr. Miklos Sajben; Dr. Thomas J. Bogar and Mr. Joseph C. Kroutil were coinvestigators. The program manager was Dr. James D. Wilson, Air Force Office of Scientific Research.

This report has been reviewed and is approved.

*R. J. Hakkinen*

R. J. Hakkinen  
Director-Research  
McDonnell Douglas Research Laboratories

*D. P. Ames*

D. P. Ames  
Staff Vice President  
McDonnell Douglas Research Laboratories

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Chief, Technical Information Division

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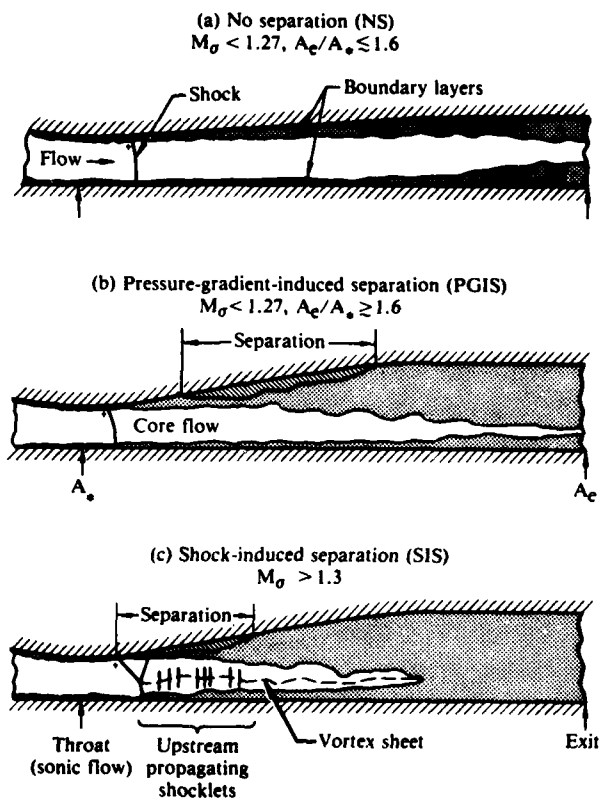
## 1. INTRODUCTION

The development of reliable theoretical prediction procedures for supersonic inlet flows requires significant experimental contributions. Detailed exploration of typical flowfields is necessary for establishing the relative importance of various flow features for modeling purposes, and extensive data sets are needed to verify theoretical predictions. Inlet performance is limited by the appearance of undesirable fluctuations; therefore, the inclusion of unsteady phenomena in both theory and experiment is necessary for the development of prediction methods that are applicable to a wide range of flight conditions.

The present program uses nominally two-dimensional, supercritical diffusers to simulate important supercritical inlet flow features. Two-dimensionality greatly extends the range of applicable diagnostic techniques and alleviates the difficulties of interpretation and analysis. At the same time, the flowfields (typical examples shown in Figure 1) contain most essential elements of their real counterparts: a normal-shock-wave/turbulent-boundary-layer interaction, a subsequent subsonic region with an adverse pressure gradient, and rapidly thickening, usually separated boundary layers which may merge well within the divergent section of the channel. Most of these flow features are constantly subjected to intensive, but isolated studies by many independent investigators. However, the interactive combination of such features displays important phenomena that involve the flow-field as a whole (e.g., large-scale, coherent oscillations). Such collective phenomena are often associated with severe technological problems and form the focus of the present study.

The accomplishments of the program have been documented extensively (Publications 1-5); the present report is restricted to a concise summary of objectives and accomplishments.





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Figure 1. Three basic types of transonic diffuser flows.

## 2. OBJECTIVES

The overall objective of the program was a broad study of the structure of transonic diffuser flows, including both time-mean and time-dependent features. Since this class of flows has not received close attention in the past, the study was necessarily exploratory.

The specific objectives of the contract are briefly stated as follows:

### First Year

Build the hardware needed to vary the thickness of the boundary layer approaching the throat of an MDRL diffuser model. Measure time-mean wall pressure and exit velocity distributions. Measure wall pressure and exit velocity fluctuations. Obtain high speed schlieren film-records of the flows. Statistically analyze the data.

### Second and Third Year

Build the hardware needed to modulate the exit area of a two-dimensional diffuser model provided by MDRL. Obtain phase-averaged wall static pressure and core flow static/total pressure distributions, as well as phase-averaged shock-position histories. Analyze and document data.

### Fourth Year

Build duct segments to vary the length of a diffuser provided by MDRL. Determine natural frequencies from shock displacement spectra and core flow lengths from internal distributions of total pressure. Develop a correlation to predict natural frequencies.

### Fifth Year

Analyze and document the data obtained in the first four years, with special attention to the process of wave reflection at the shock, the apparent absence of resonance in forced oscillatory tests, and the intermittent behavior characterizing the onset of shock-induced separation.

### 3. DESCRIPTION OF EXPERIMENTS

Two different diffuser models were used: one with an exit-to-throat area ratio ( $\alpha$ ) of 2.37 (referred to as model B, Figure 2 and Publications 1 and 2), and another with  $\alpha = 1.5$  (referred to as model G, Figure 3, and Publications 2-5). Both were investigated over comparable ranges of the Mach number immediately before the shock ( $M_o$ , from 1.1 to 1.4), which was found to be the primary variable determining the character of the flow.

If  $M_o$  is over a configuration-dependent critical value (1.3 for model B and 1.28 for model G), then shock-induced separation (SIS) occurs at the foot of the shock (strong shock, Figure 1c, References 1-4). For shock Mach numbers below 1.3 for model B and 1.27 for model G) the type of flow depends on the model. In the case of the moderate-area-ratio model G, there was no separation (NS) present on either wall (Figure 1a); in model B, with a considerably greater area ratio, pressure-gradient-induced separation (PGIS) occurred on the top wall at locations distinctly downstream of the shock (Figure 1b). All investigated flows could be classified as one of the three types shown in Figure 1.

The flow in model B exhausted directly to the laboratory, so that the boundary condition over the exit cross section was closely characterized as

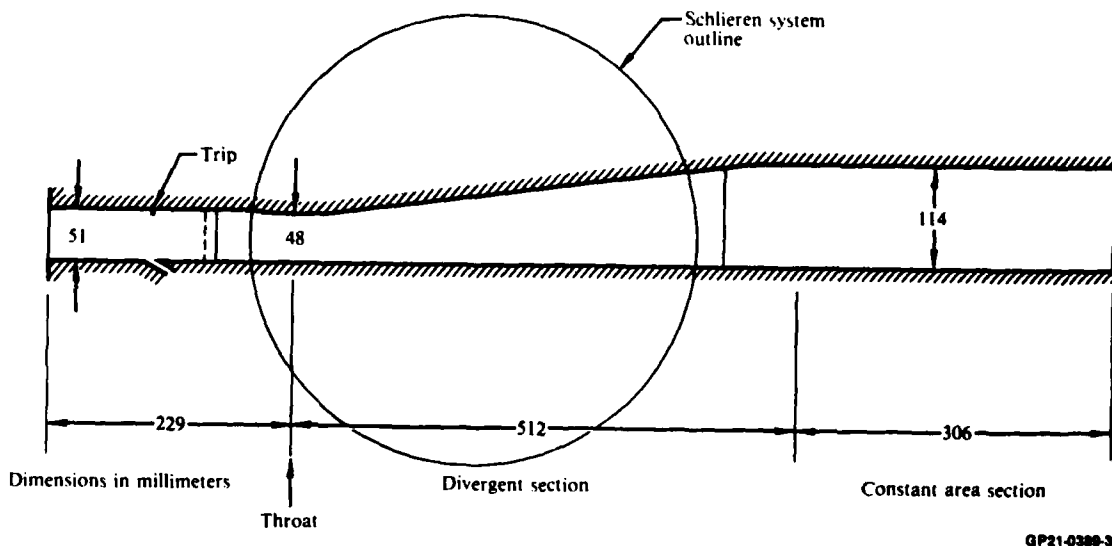


Figure 2. Diffuser Model B. Area ratio = 2.37.

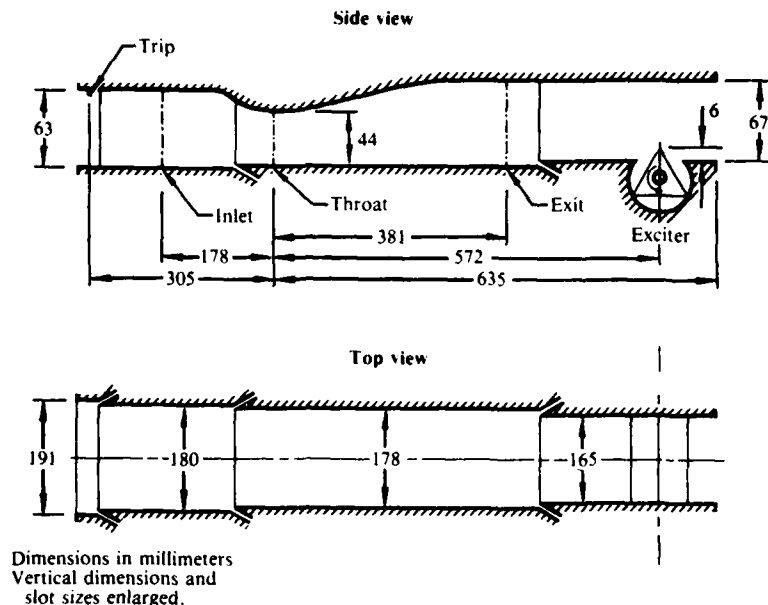


Figure 3. Diffuser model G with rotary exciter. Area ratio = 1.5.

spatially and temporally constant static pressure. Model G could be operated in the same way, or its exit cross-sectional area could be modulated at frequencies up to 340 Hz using the rotary device shown in Figure 3, thereby imposing an external, periodic perturbation on the flow. Unsteady flows created by such controlled disturbances serve as computational test cases with deterministic time-dependence, and also simulate oscillatory flows in ramjet inlets driven by combustion instabilities.

As illustrated in Table 1, the six possible combinations formed by the two types of boundary conditions (steady or periodic) and the three types of flow patterns (NS, PGIS, and SIS in Figure 1) define six major classes of flows, five of which were explored in this program.

The thickness of the initial boundary layer and the length of the diffuser channel were additional test parameters.

Flow visualization by high-speed shadowgraph and schlieren photographic methods has been used extensively throughout the program, providing valuable characterization of the dynamics of the system. An MDRL-developed optical system that indicates shock position in real time allowed a reliable spectral

**TABLE 1. TYPES OF SUPERCRITICAL DIFFUSER FLOWS AND THE MODELS (G, B) IN WHICH THEY OCCURRED.**

	Top-wall boundary layer	Attached	Separated	
	Shock Mach number	Weak ( $< 1.28$ )		Strong ( $> 1.3$ )
	Designation (See Figure 1)	NS	PGIS	SIS
	Exit boundary condition			
	Steady	G	B	G, B
	Periodically modulated	G	—	G

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analysis of shock displacement fluctuations. Much dynamic pressure information was acquired from wall-mounted static-pressure and immersed static/total pressure sensors.

Figure 4 illustrates the types of data obtained, classifying them according to their dependence on time. Random signals were treated by methods of classical statistics, particularly by calculating power spectral density distribution functions. Low-frequency peaks in these distributions identified preferred (natural) oscillation frequencies, whose dependence on various test parameters was of particular concern. Periodic oscillations occurred in model G when excitation was applied; time-records obtained under these conditions were subjected to averaging over many cycles to separate the periodic part of the signal from random contributions. The periodic part, not generally sinusoidal, was Fourier-decomposed to determine the (generally dominant) first harmonic. Unlike the noisy raw signals, the phase and amplitude of the first harmonic components displayed clearly identifiable trends that could be compared meaningfully with theoretical predictions.

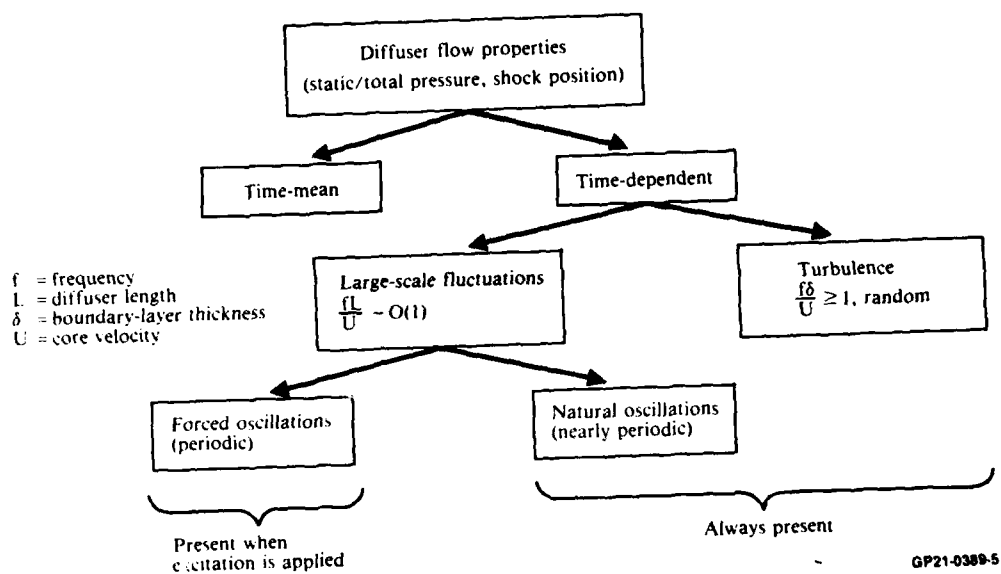


Figure 4. Classification of flow properties.

#### 4. REVIEW OF RESULTS

A summary of research conducted under this contract is given in Table 2.

TABLE 2. CONTRACT SUMMARY.

Area of investigation	Contract year	Documentation
Effect of initial boundary-layer thickness	1977/78	Publications (1), (2)
Effects of shock strength and duct length on natural frequencies	1980/81	Publication (3)
Response of diffuser to periodic perturbations imposed at the downstream end	1978/80	Publication (4)
Analysis of factors influencing time-mean distortion	1981/82	Publication (5)
Analysis of wave reflection and resonance effects	1981/82	

##### 4.1 Effect of Initial Boundary Layer Thickness

This study, conducted in the first year using model B (Publications 1 and 2), led to the following principal conclusions:

The influence of the approach boundary-layer thickness on nominally two-dimensional transonic diffuser flows depends on shock strength.

If the Mach number before the shock is less than approximately 1.3, flow separation occurs well downstream of the shock, i.e., separation is induced by the adverse pressure gradient in the subsonic flow (PGIS). In this situation, the boundary-layer thickness has a significant but moderate influence on both the time-mean and fluctuating flow properties. As the boundary-layer displacement thickness increases, separation occurs earlier, reattachment occurs later, static and total pressure recoveries are reduced (Figure 5), and the three-dimensional features of the flow are intensified. Shock displacement amplitudes increase dramatically, but frequencies increase only slightly. Surface pressure fluctuations change minimally.

Shock Mach numbers greater than approximately 1.3 involve a pressure jump large enough to cause immediate separation (SIS). An increase of the initial displacement thickness under this condition generally results in consequences similar to those for weak shocks. However, the magnitude of the effects is

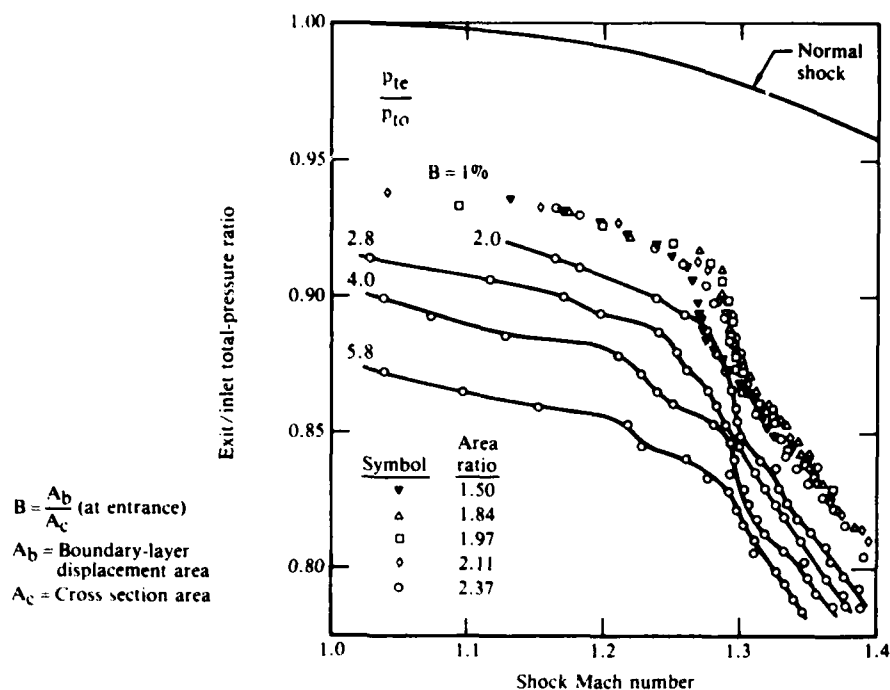


Figure 5. Supercritical diffuser losses.

much smaller, and for several flow properties (e.g., surface pressure fluctuation) there is virtually no effect.

One valuable byproduct of this investigation was the experimental demonstration of earlier expectations that the wall pressure fluctuations originate from two distinct mechanisms. One source is a large-scale fluctuation that is coherent along most of the diffuser. This source accounts for a large, low-frequency contribution near 100 Hz. The second source is the local turbulence in the shear layer whose dominant frequency range varies widely along the channel from  $\approx 6000$  Hz near the shock to  $\approx 300$  Hz near the end of the divergent section. Except for low-frequency-dominated locations near the shock, the two contributions are of comparable intensity.

The turbulence frequencies decrease in the streamwise direction, near the duct end they are sufficiently low to interact with the large-scale, coherent oscillation and are probably the reasons for its presence. Flows in model B, therefore, contain large regions in which the time scales of turbulence and the time scale for the unsteady mean motion are comparable. The time-



dependent theoretical description of flows in this class may therefore require a model capable of describing at least some details of the large eddies in the flow.

#### 4.2 Factors Determining Natural Frequencies

This work was completed in the fourth year of the contract, using the moderate-area-ratio model G. The results are documented in Publications 3 and 4. The diffuser displayed attached flows (NS) below a shock Mach number of 1.27 and a shock-induced separation (SIS) above 1.28, with an intermittent transition between these limits. Broadband pressure and narrowband shock displacement oscillations occurred at all conditions with relatively small amplitudes compared with earlier experiments with model B and with other larger area-ratio diffusers (Publication 5).

For attached flow, the natural frequencies in the unsteady shock motion scale inversely with the shock-to-exhaust distance, which was varied from 15 to 30 throat heights. The mechanism of the oscillation is propagation of acoustic waves along the channel in both directions. Modes up to the third harmonic are observed. The frequencies of these oscillations are well predicted by inviscid, one-dimensional, linearized (acoustic) calculations.

In case of shock-induced separation (SIS), both pressure and shock displacement amplitudes are greater, and only one natural frequency is observed. The natural frequency of this oscillation mode is independent of duct length and is not predicted by acoustic theory; the responsible mechanism is not clear. The frequency appears to scale with the length of the inviscid core flow and is related to convective effects in the boundary layer (Reference 5). The observations, however, also admit another explanation that links the natural frequency to the low-pass-filter-like response of the terminal shock as it reacts to the broadband pressure fluctuation environment created by the highly turbulent, separated boundary layers.

#### 4.3 Response to Periodic Perturbation Introduced at the Downstream End

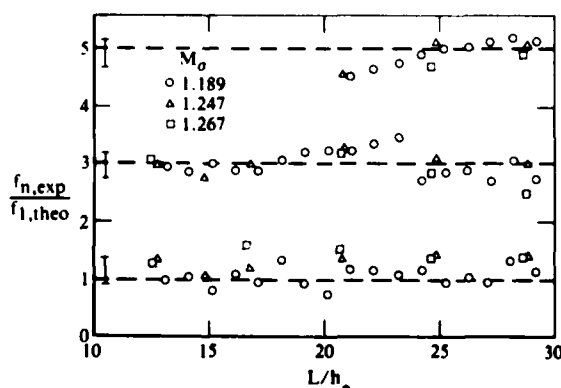
This study was conducted in the second and third years of the contract, using model G and the simple mechanical exciter illustrated in Figure 2. The results are documented in Publication 4.

The periodic pressure fluctuations were generally less than 2% of the local static pressure throughout the diffuser. The amplitude and phase angle distributions of the imposed pressure and velocity perturbations were calculated from the data for several excitation frequencies, both with and without shock-induced separation. A sample for the latter is shown in Figure 6.

The results show that neither the mean flow nor the time-mean value of the naturally present fluctuation intensities is altered appreciably by the superimposed perturbations. No obvious resonance effects were observed when the excitation frequency was near any of the well-defined natural frequencies determined from natural shock displacement spectra.

The character of the forced perturbation field depends on whether the shock is weak ( $M_G < 1.27$ , NS) or strong ( $M_G > 1.28$ , SIS).

The determining factor is the type of the reflection of the impinging pressure wave off the shock. In the weak shock case, there is no significant reflection. Pressure waves propagate upstream with approximately the velocity of acoustic waves ( $a - u$ ), but there is no evidence in the pattern of a return wave. In the strong shock case, the pressure perturbation pattern within the channel shows significant, localized phase shifts coinciding with minima in the pressure amplitude distribution. This behavior can occur only when the reflection off the shock is significant.



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Figure 6. Comparison of Model G natural frequencies with one-dimensional, acoustic predictions using reflection coefficients for plane, normal shocks.  $L$  = diffuser length,  $h_0$  = throat height.

The interaction of perturbations with a normal shock (reflection) is complex, depends on shock strength, and differs from the reflection process found with natural oscillations. The findings justify the conclusion that reflection modeling is a key problem in the further development of prediction methods suitable for engineering purposes.

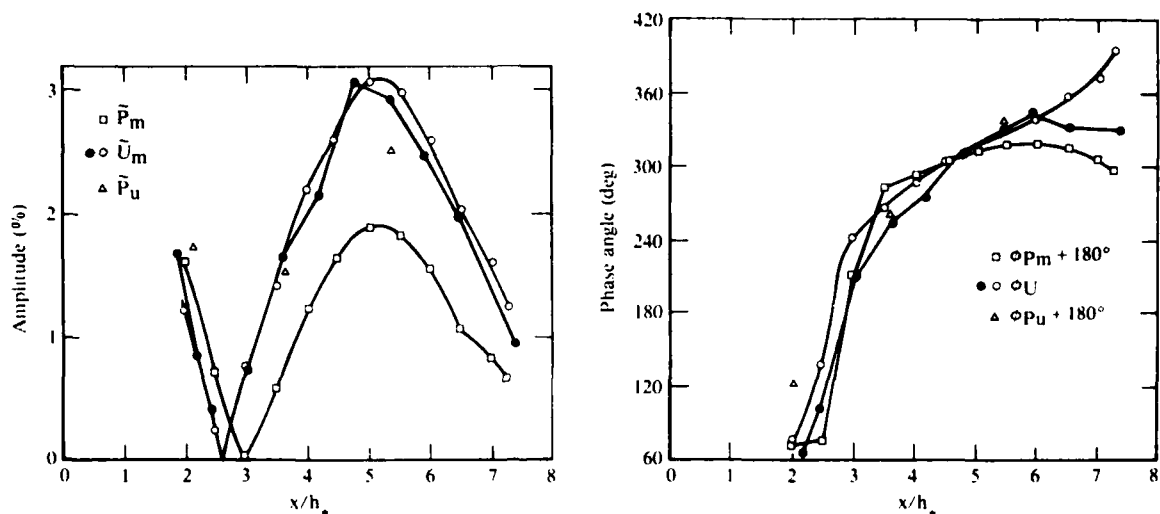
These results may be dependent on the method of excitation employed. In particular, the apparent lack of resonance may be attributed to the possibility that asymmetric excitation leads to a mode of oscillation different from the natural mode.

#### 4.4 Wave Reflection at the Shock; Resonance

The fifth year of the contract was devoted to organizing and documenting the large amount of experimental information obtained in prior years, including the streamlining of data files and the preparation of meeting papers and journal articles. The material was also subjected to further analysis to extract implicit information concerning selected, important physical mechanisms: wave reflection and resonance.

The appearance of related studies based on acoustic theory (Reference 10) supplied a timely framework for the characterization of boundary conditions represented by the terminal shock. After rederiving the results of Reference 10 (and correcting minor discrepancies), the theory was used to calculate the complex reflection coefficients for a plane shock located in a mildly varying area channel. The reflections are typically weak, amounting to less than 1% of the incident wave for the present experiments. The shock is thus predicted to act as a nearly anechoic termination which extracts almost all of the energy contained in the incident wave. The loss of energy damps the fluctuations.

The reflection coefficients were used to calculate the natural frequencies of attached model G flows. The results agree with experimental data within the experimental uncertainty (Figure 7).



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Figure 7. Streamwise distribution of amplitude and phase angle ( $\phi$ ) for the first harmonics of static pressure ( $\bar{P} = \gamma p' / \bar{p}$ ) and velocity ( $\bar{U} = u' / \bar{a}$ ). Subscript m refers to midstream (within core flow) and u to upper wall. Model G,  $M_o = 1.353$ , shock-induced separation present,  $f = 300$  Hz.

For attached flows, the streamwise distributions of pressure perturbation amplitudes in forced oscillation experiments agree well with the predictions of acoustic theory, but velocity distributions show systematic deviations. Considering all available information, the deviations are interpreted to reflect transverse, traveling waves in the boundary-layer/core flow interface. Such motions are closely linked to vorticity perturbations that are not represented by one-dimensional acoustic theory.

Undulations of the boundary layers are known to dominate the fluctuations occurring in the SIS mode (Reference 5). Under such conditions, the pressure and velocity perturbation amplitude patterns in the forced oscillation experiments clearly indicate strong reflections at the shock. Absolute values of the reflection coefficients are near unity, far beyond what could be attributed to planar-shock/acoustic-wave interactions. Both the perturbations and their reflections from the shock strongly involve the wall boundary layers. No simple physical model capable of correlating the experimentally observed reflections was found.

The absence of a singular response to excitation near the natural frequencies led to further examination of the conditions under which resonance might occur in the investigated diffusers. The study used several simple

mathematical models for channel flow, approximating end-conditions, loss mechanisms, and convective effects in various ways. Detailed consideration was given to a perturbed form of the integral energy equation expressing the fluctuating energy contained within the diffuser volume. The derived expressions show the significance of the presence of a mean flow and the limited applicability of the classical acoustic energy equation to the problem at hand.

The conclusions of the study are briefly described as follows: the concept of resonance is precisely defined in the context of continuous systems described by the linearized wave equations, with or without some distributed dissipation (damping). This clarity is lost if the system is influenced by physical mechanisms other than wave propagation, described by a correspondingly more complex mathematical formulation. The pressure/velocity perturbation field investigated here significantly involves convection of inherently transverse disturbances (vorticity), dissipation in intensely turbulent regions, and possibly large losses of energy through the shock which forms the upstream boundary of the region. These factors often dominate over wave propagation, obscuring the concept of resonance. Discrete natural frequencies are replaced by broad-band responses, and the choice of proper dimensionless parameters to describe dynamic phenomena becomes difficult.

The conclusion is that a careful redefinition of the concept of resonance is required, generalizing it to conditions that are significantly affected by mechanisms other than wave-propagation. The formulation of such a definition is a broad, basic question relevant to many compressible flows, and its study was considered beyond the scope of this contract.

The question of resonance is relevant from the research point of view, but finding the answer is not an absolute necessity in the development of a given design. An adequate substitute for engineering purposes may be to establish the maximum shock displacement and post-shock pressure fluctuation amplitudes as functions of exit pressure amplitude and frequency. Suitable nondimensional representations are discussed.

## 5. SUMMARY

The significant accomplishments of this program are:

- definition of a fluid mechanical experiment that models dominant features of supersonic inlet flowfields at a manageable level of complexity and can be directly related to state-of-the-art theoretical efforts;
- application of fluid mechanics research methods to characterize inlet-like flowfields which are usually treated by engineering methods aimed at determining overall performance;
- exploration of controlling parameters to an extent sufficient to determine major dependencies, identify critical areas, and aid the modeling process in constructing prediction methods;
- explicit consideration of large-scale natural fluctuations;
- exploration of dynamic response to controlled external perturbations over a frequency range including the natural frequencies; and
- coordination of the experimental work with requirements of numerical code development and generation of data suitable for verification of codes for both steady and time-dependent flows (References 6-9).

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